Towards a Consistent Conventional Treatment of Surface-Load Induced Deformations

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Towards a Consistent Conventional Treatment of Surface-Load Induced Deformations

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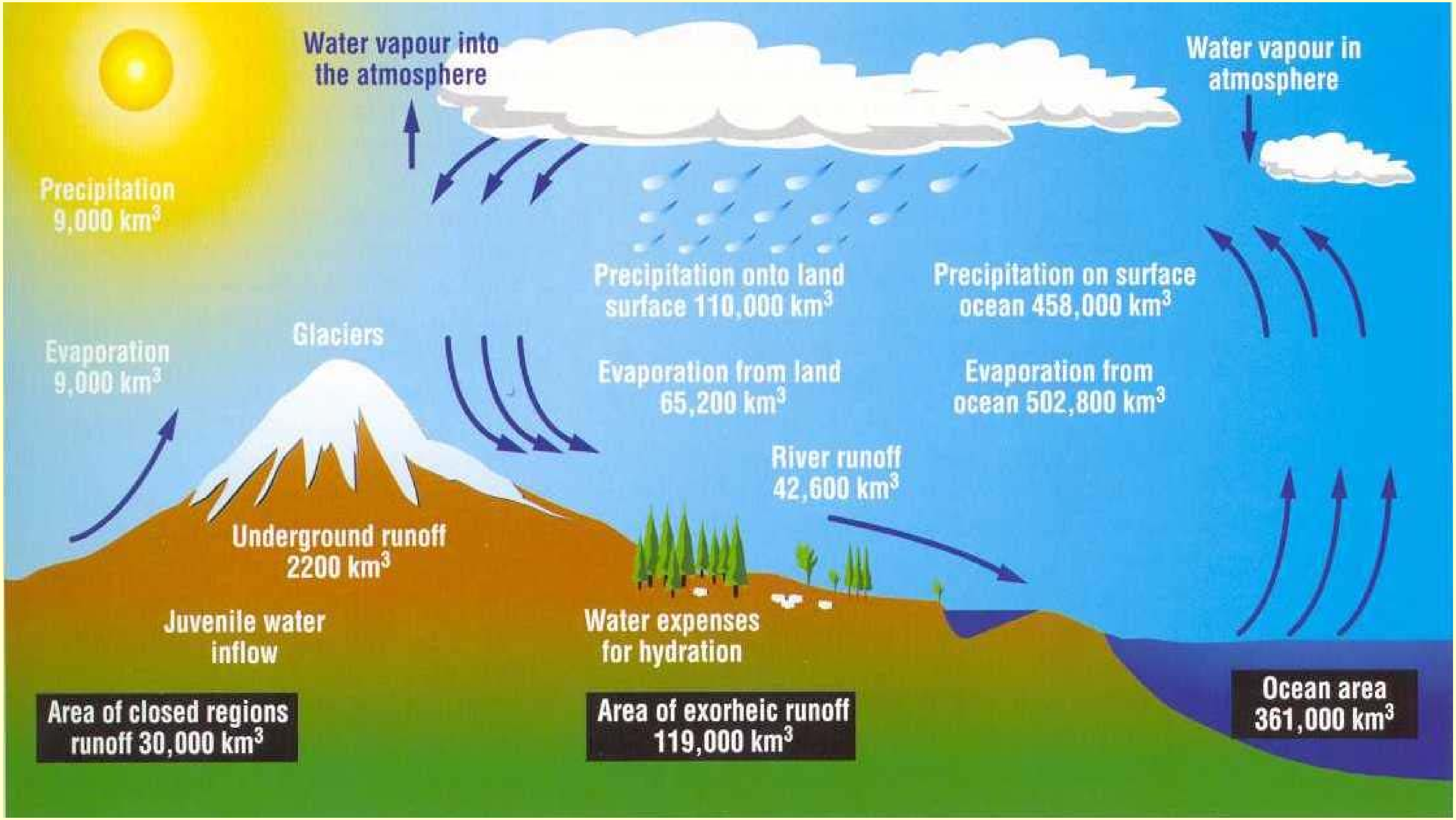
Introduction



At time scales from sub-daily to decades, the largest mass redistributions on the surface of the solid Earth mainly occur in the global hydrological cycle, i.e., the water stored in atmosphere, ocean, on land, in glaciers, and ice sheets.

Introduction

S1: The geodetic signals of mass redistribution in the global hydrological cycle need to be modeled in a gravitationally consistent integrated model of the Earth system accounting for the linkage between reservoirs in the hydrological cycle as well as the feedback of the changes in Earth's shape, gravity field and rotation on the distribution of mass in these reservoirs.

Introduction

Determination of ITRF:

- Polyhedron with the motion of the vertices given as “regularized coordinates”:

$$\vec{X}^{(i)}(t) = \vec{X}_0^{(i)} + \vec{V}_0^{(i)} \cdot (t - t_0)$$

- $\vec{X}_0^{(i)}, \vec{V}_0^{(i)}$: affected by station motion model, troposphere & ionosphere treatment, antenna model, analysis strategy, ...

Access to the ITRF:

- Through satellite orbits and clocks and EOP.
- These global parameters are affected by station motion model, ...
- Should be the same as used for the determination of the $\vec{X}_0^{(i)}, \vec{V}_0^{(i)}$

Introduction

- Station motion model (depending on length of analysis interval):

$$\vec{X}(t) = \vec{X}_0 + \sum_{k=1}^{K} g_k(t, \vec{X})$$

$$\vec{X}(t) = \vec{X}_0 + \vec{V}_0 \cdot (t - t_0) + \sum_{k=1}^{K} g_k(t, \vec{X})$$

- Conventional models:
  (1) Earth tides,
  (2) ocean tidal loading,
  (3) pole tide
  Contributions not included in the reference and station motion model are globally filtered!

- Potential extensions (station motion model or regularized coordinates):
  - atmospheric tidal loading
  - atmospheric loading
  - ocean non-tidal loading
  - terrestrial water storage

Introduction

S2: A conventional approach to load-induced geodetic signals based on **separate models** for the main reservoirs of the global hydrological cycle will **not meet** the accuracy and consistency goal of 1 ppb.

The Goal

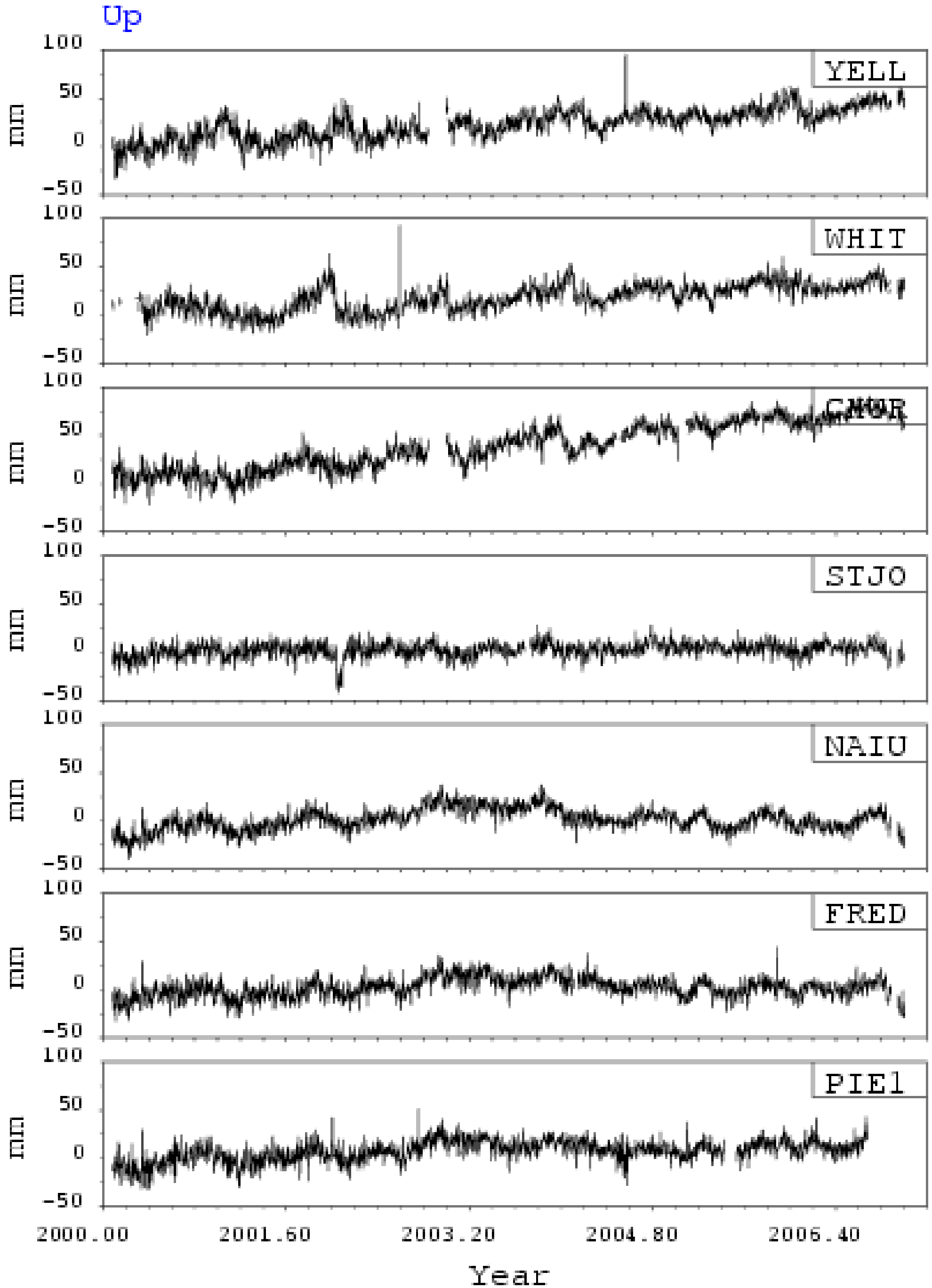
S3: Condensing the essential goal of a global terrestrial reference frame, we state that while the primary goal in the **past** was to allow for the determination of **point position**, the primary goal **today** is to allow for the monitoring of **point motion**.

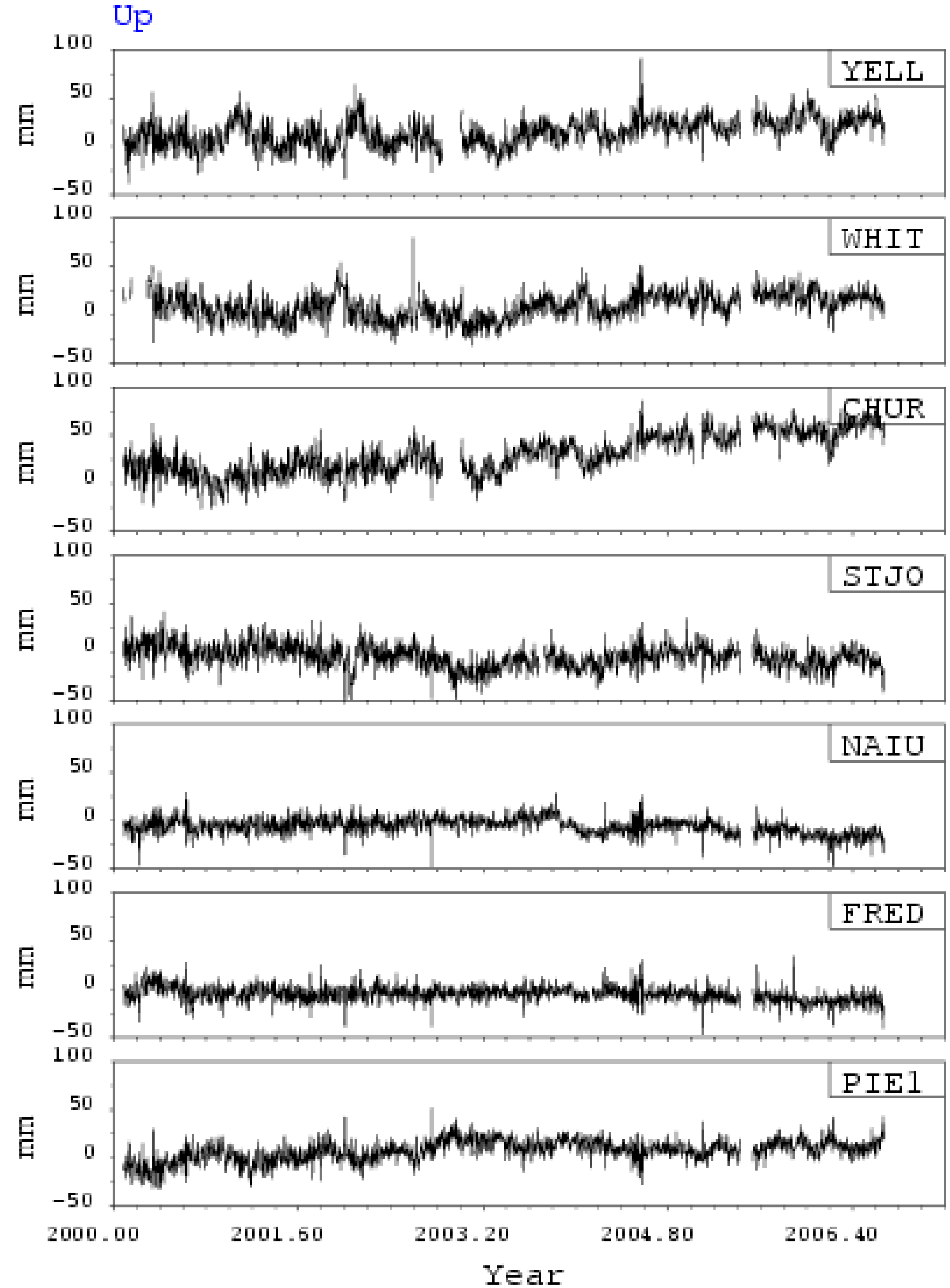
Concept of “anomalous motion”:

- Deviation from the predicted motion.
- High demands on quality of predicted motion.

The Problem

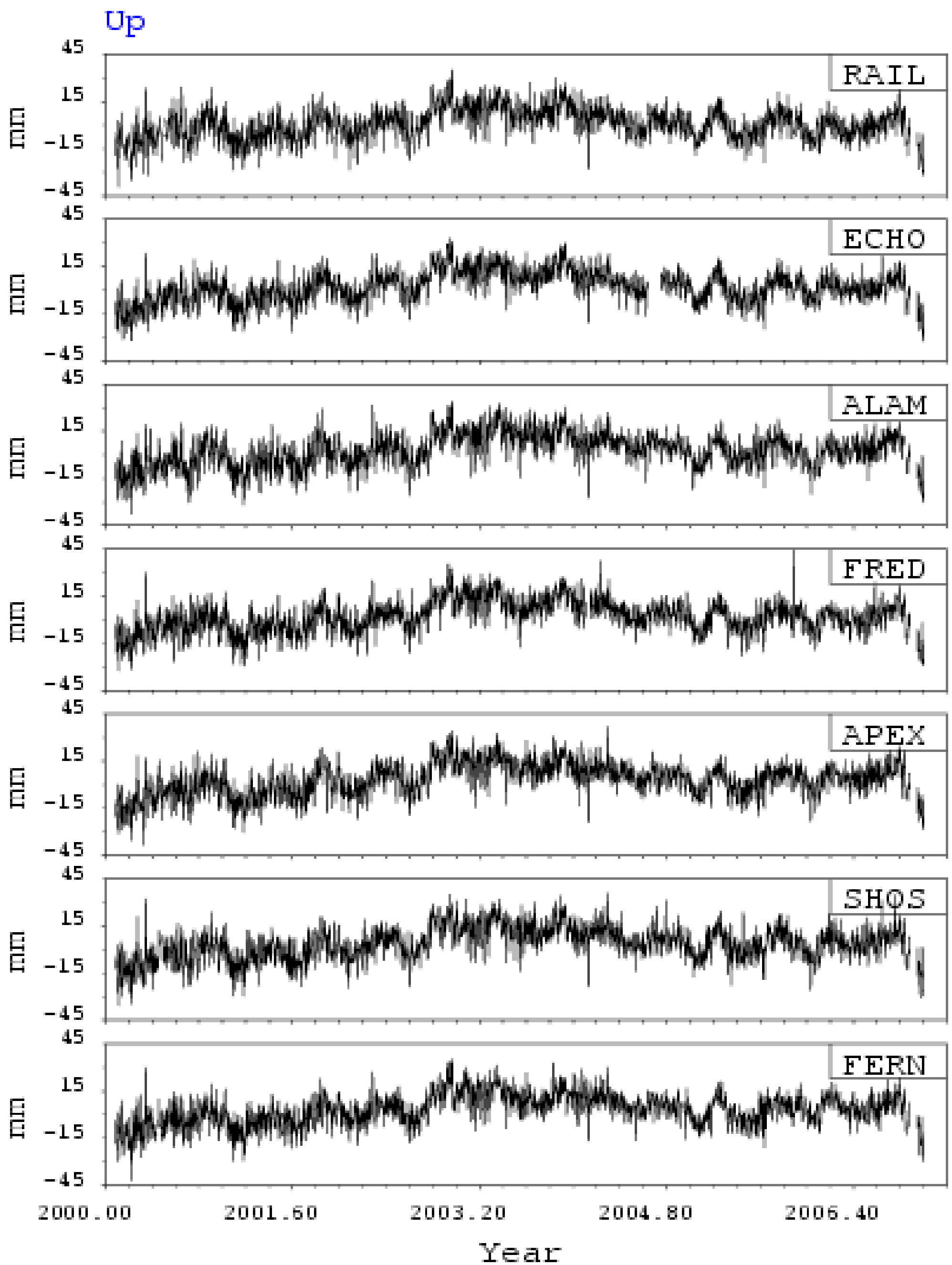
Differences to PIE1

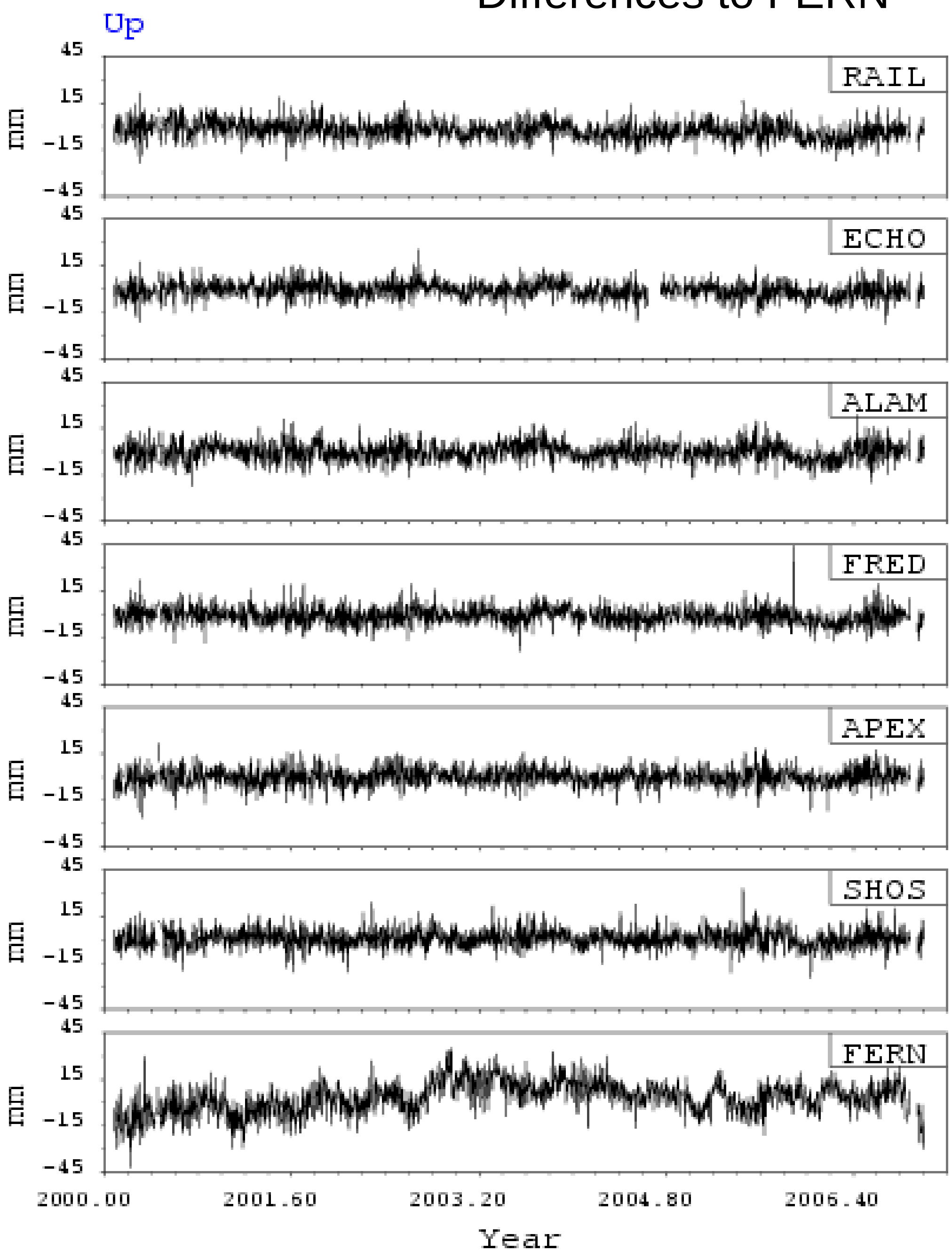




The Problem

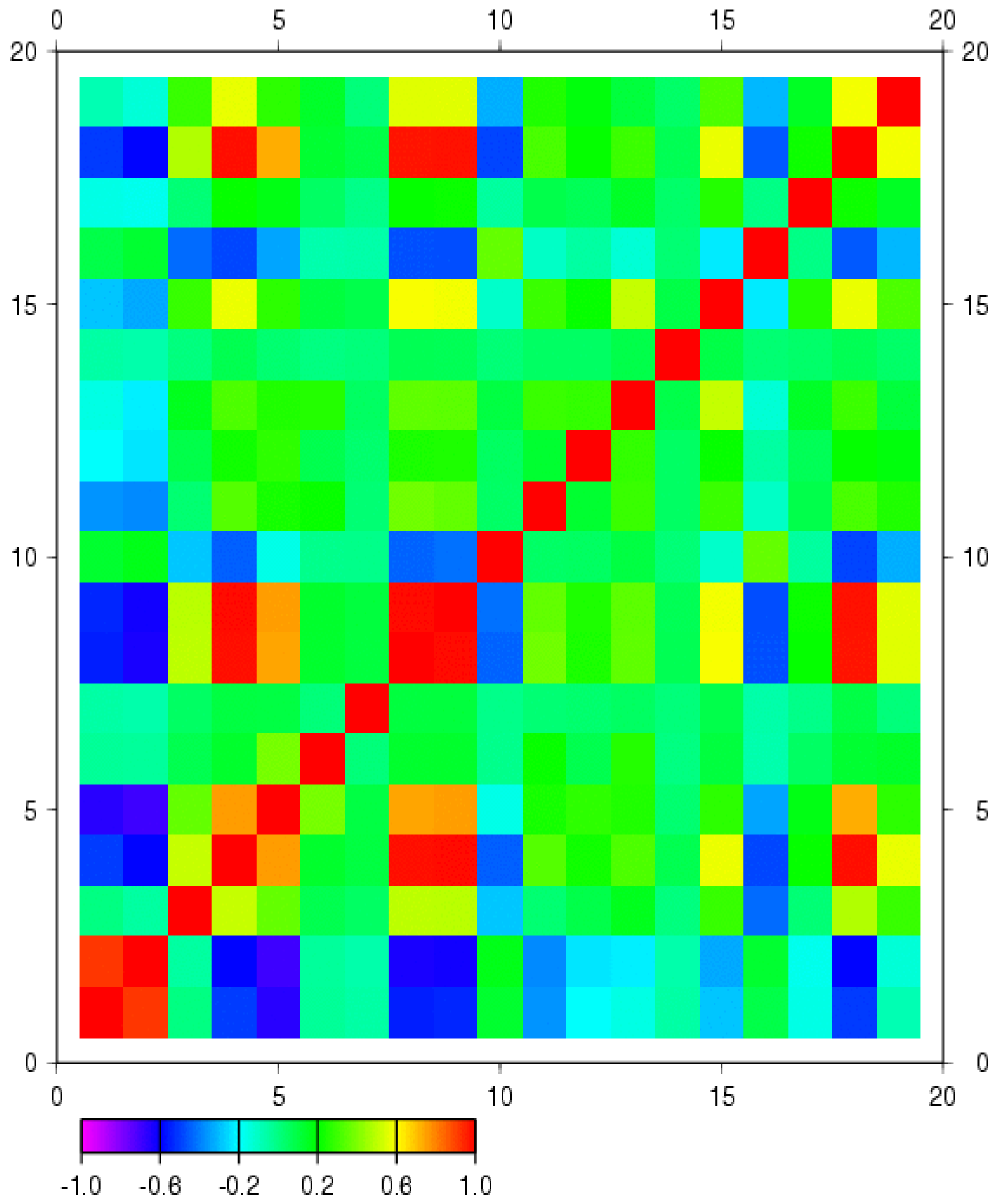
Differences to FERN





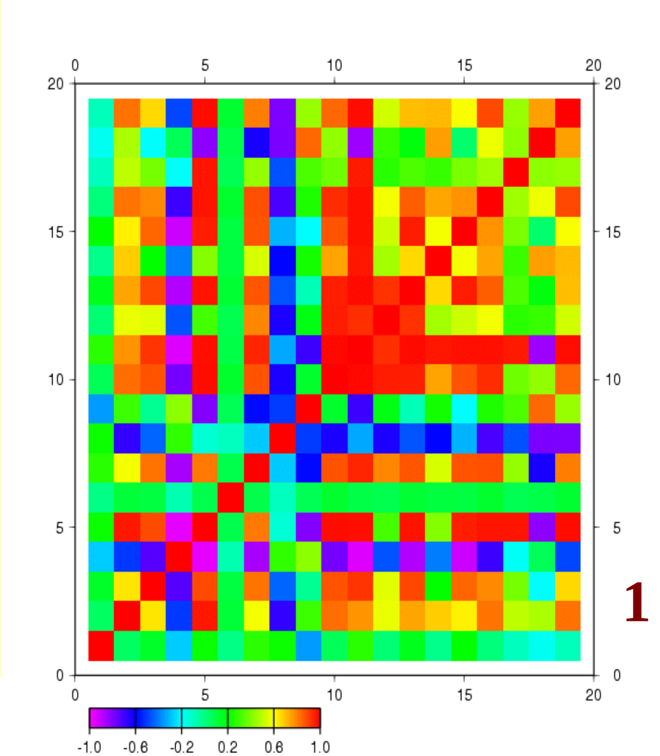
The Problem

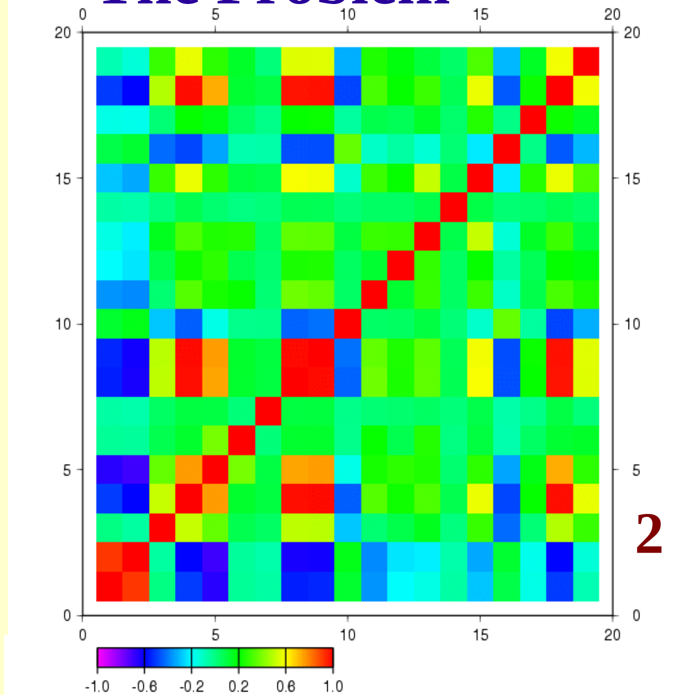
Cross-correlation between time series of vertical displacements
Analysis: UNOTT-R

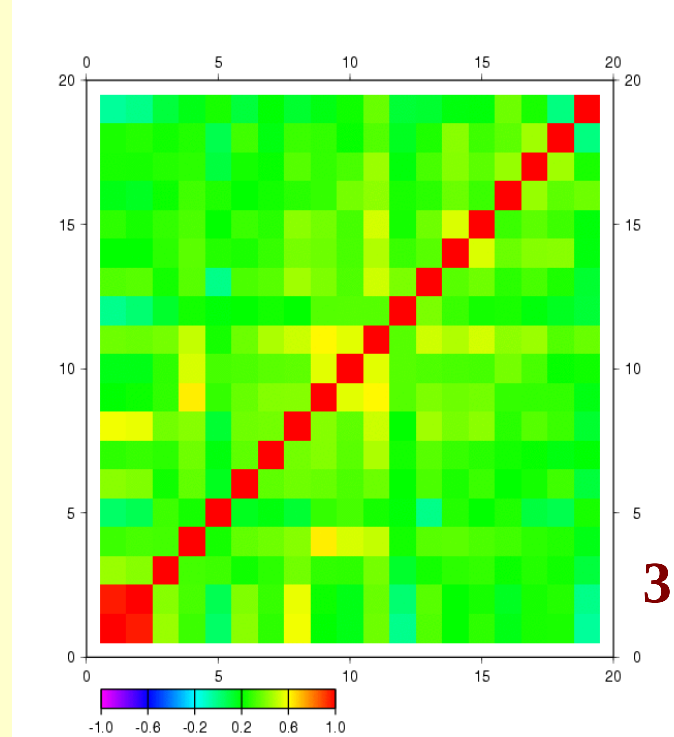


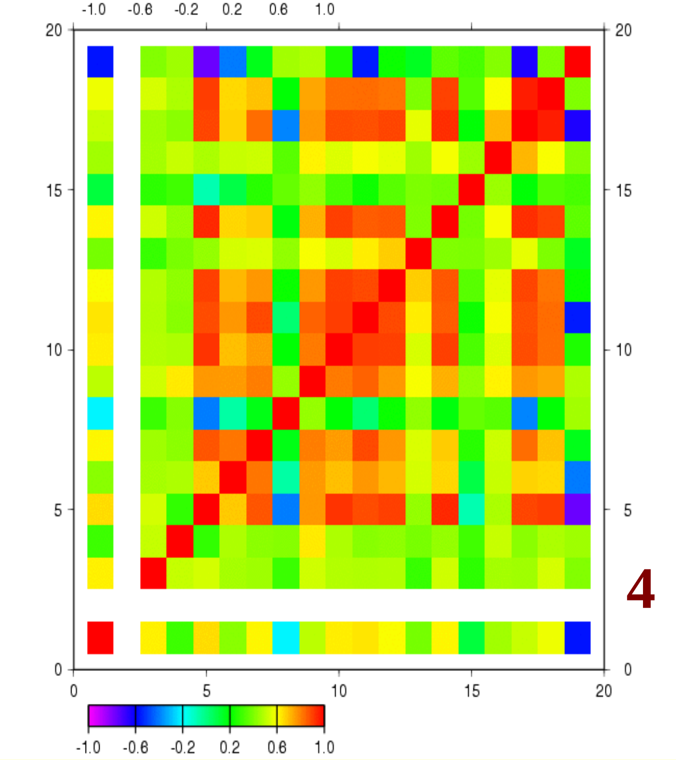
1	nya1	78.92956	11.86531
2	nyal	78.92958	11.86508
3	ando	69.27837	16.00870
4	helg	54.17448	7.89309
5	wlad	54.79676	18.41875
6	morp	55.21279	358.31451
7	nstg	55.00742	358.56012
8	live	53.44970	356.98178
9	lowe	52.47322	1.75020
10	shee	51.44568	0.74341
11	pmtg	50.80233	358.88879
12	camb	50.21844	354.67264
13	newl	50.10303	354.45721
14	alac	38.33892	359.51877
15	lago	37.09894	351.33163
16	geno	44.41939	8.92114
17	cagl	39.13591	8.97275
18	lamp	35.49977	12.60566
19	vene	45.43698	12.33198

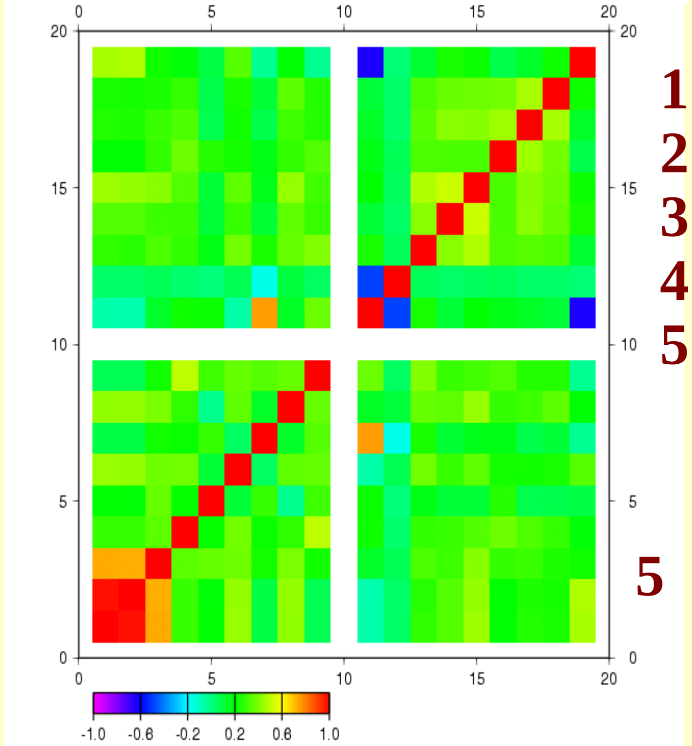
The Problem











1: NMA-IGS (GIPSY/IGS)
2: UNOTT-R (Bernese)
3: GCM-G (GAMIT)
4: SRC-R (Bernese)
5: NGL/UNR (GIPSY/JPL)

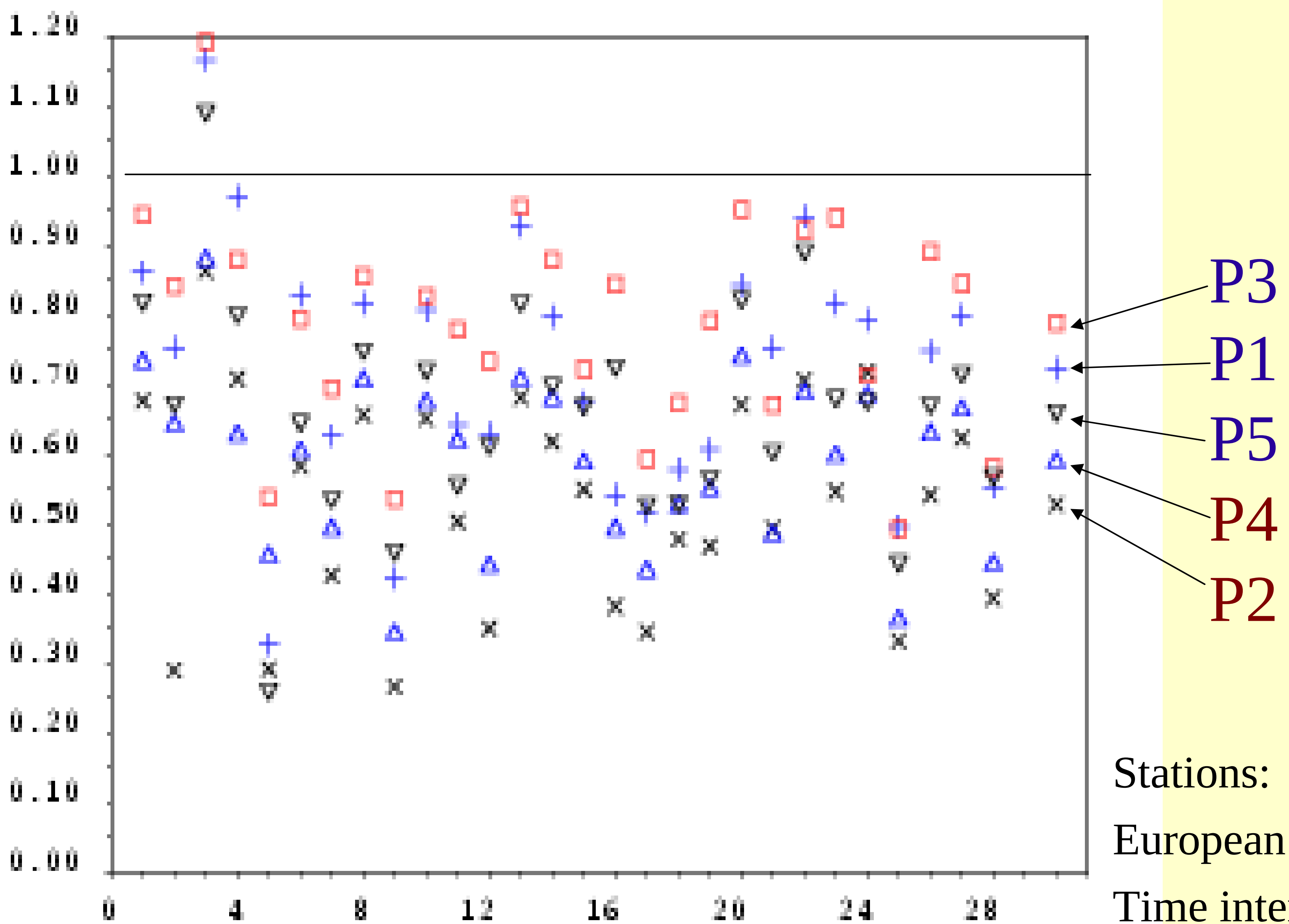
The Problem

Pred.	Input	RFO	Earth Model	Convolution	Author
P1	ECMWF	CE	PREM	SHE	PG
P2	ECMWF	CM	PREM	SHE	PG
P3	NCEP	CE	PREM	SHE	PG
P4	NCEP	CM	PREM	SHE	PG
P5	NCEP	CE	G+B	CGF	TvD

RFO: Reference Frame Origin
CE: Center of mass of the solid Earth
CM: Center of mass of the whole Earth system
G+B: Gutenberg - Bullen
SHE: Summation of spherical Harmonic Expansion
CGF: Convolution of Green's Function and load anomaly
PG: Pascal Gegout
TvD: Tonie van Dam

Source: http://www.sbl.statkart.no/

The Problem



Regression Coefficients for time series of observed and predicted vertical displacements

Stations: European CGPS

Time interval: 2000.0 - 2004.0

The Problem

S4: Space-geodetic time series of Earth's surface point displacements contain non-geophysical signals and sub-daily to decadal geophysical signals are significantly biased.

The Proposal

Extending the reference frame concept:

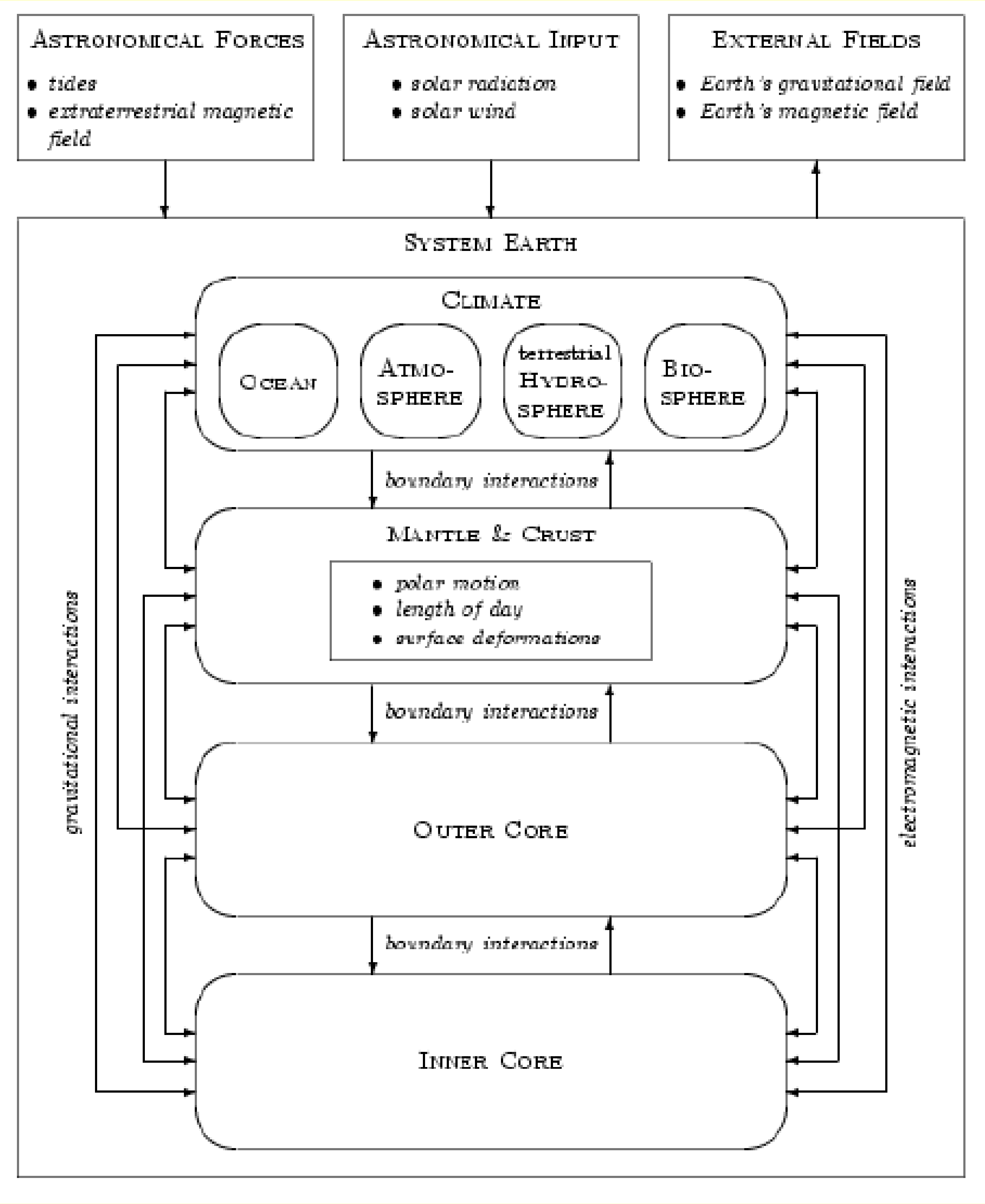
- Dynamic Reference Earth Model (DREM)
- Reference motion for any point on Earth:

$\vec{X}(t) = \vec{X}_0 + \delta\vec{X}(\vec{X}_0, t)$ (or potentially $\vec{X}(t) = \vec{X}_0 + \vec{V}_0(\vec{X})(t - t_0) + \delta\vec{X}(\vec{X}_0, t)$)

with $\delta\vec{X}(\vec{X}_0, t)$ predicted by the DREM

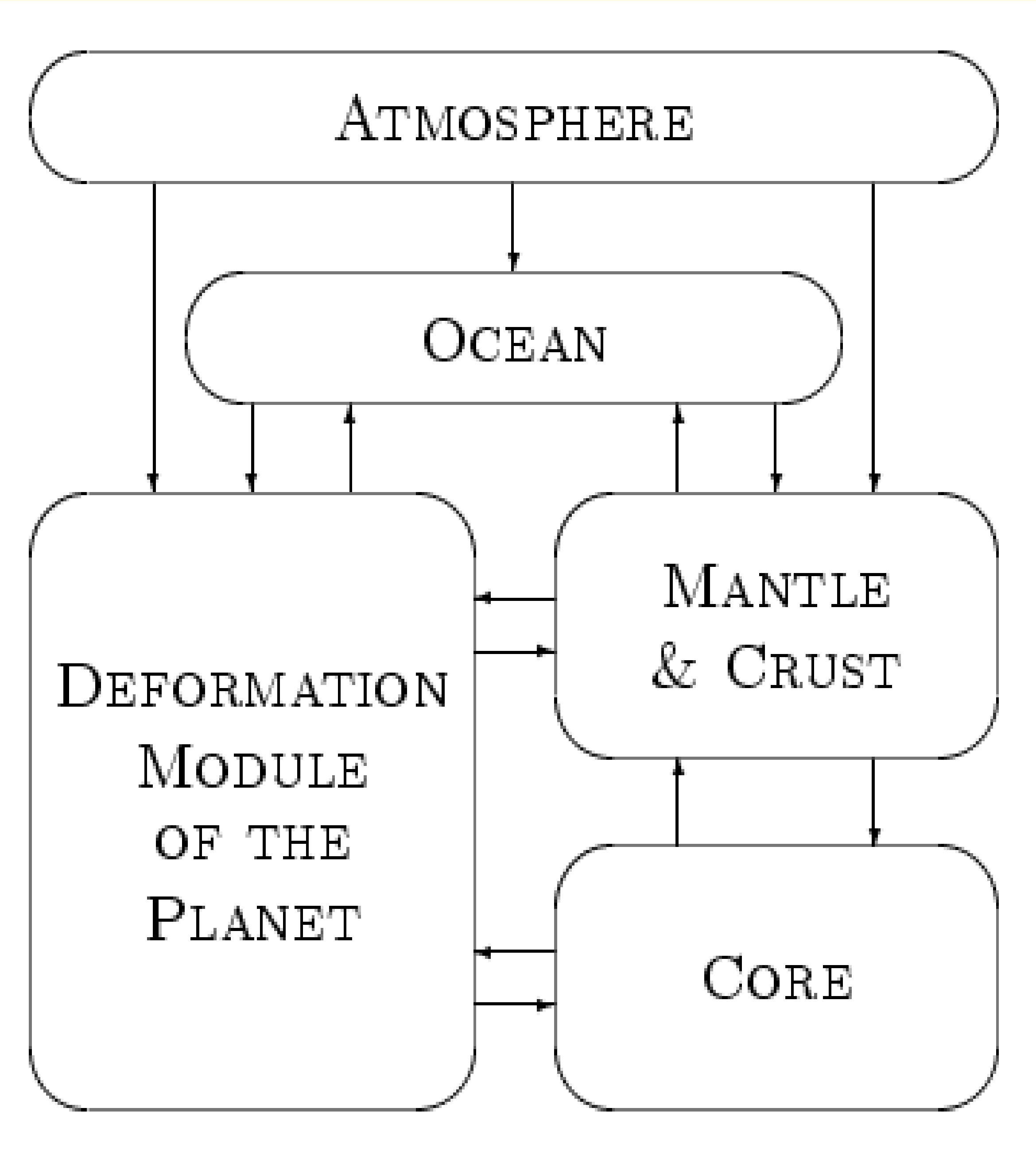
S5: In order to capture geophysical signals unbiased and unmodified in space-geodetic time series of surface displacements, a reference frame approach based on a dynamic reference Earth model is required.

Considerations Concerning a DREM



- Complex system
- Modular approach to modeling
- Comparable to climate modeling
- Independent modules interact through surface and volume forces

Considerations Concerning a DREM



- Complex system
- Modular approach to modeling
- Comparable to climate modeling
- Independent modules interact through surface and volume forces
- Previously used for Earth rotation (Juettner & Plag, Thomas et al., Seitz et al.)

Steps towards DREM:

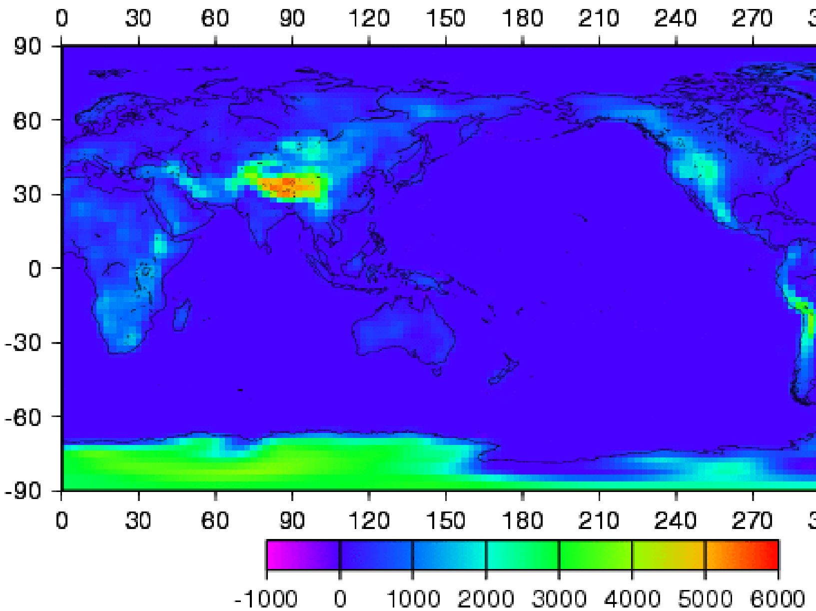
- Solid Earth coupled to ocean, atmosphere and terrestrial hydrosphere models
- Mass conservation

Challenges:

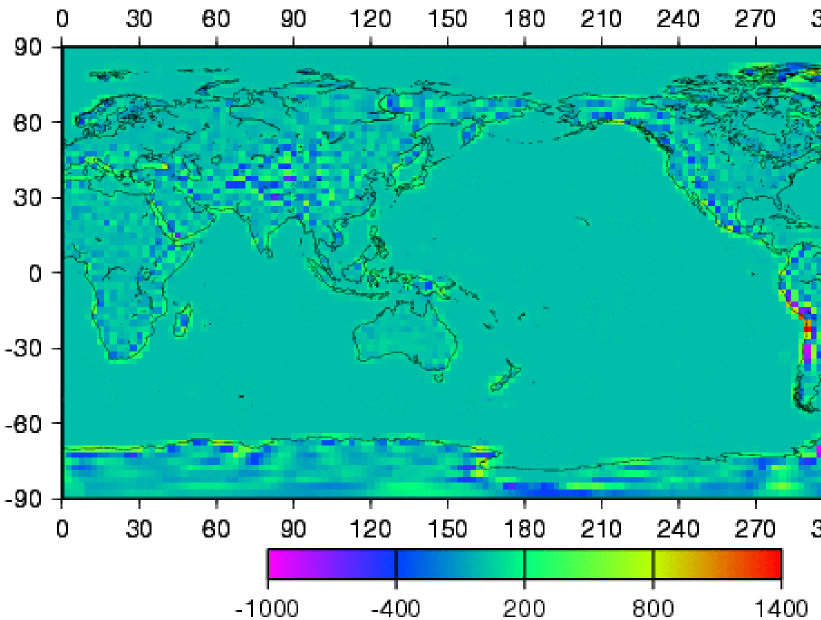
- Reference frames for modules
- Theory for initial value problem
- Data assimilation

Challenges

NCEP Model Orography



NCEP - ETOPO5



Challenges:

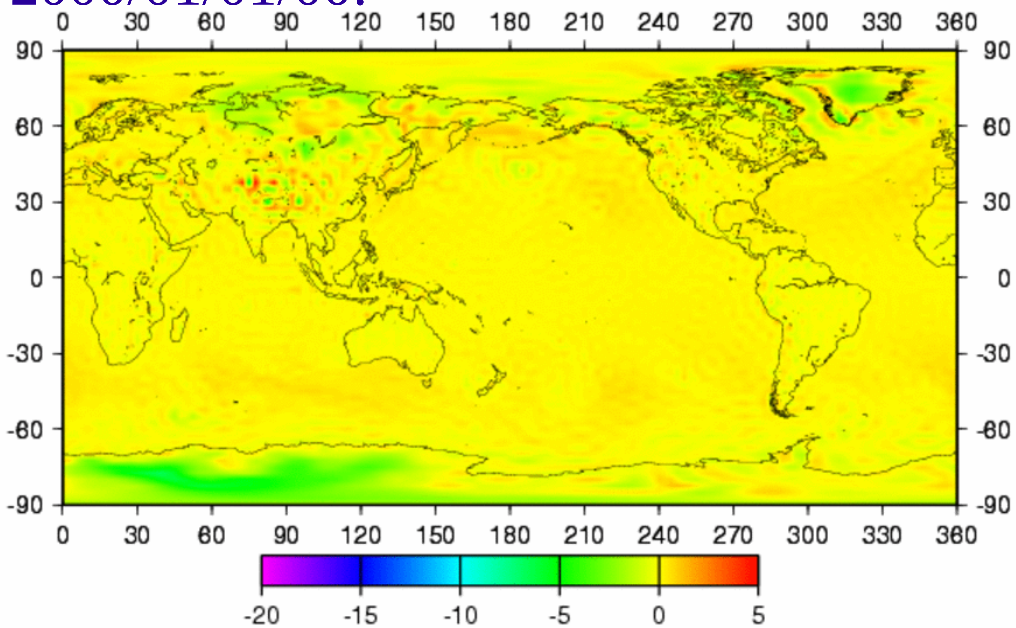
- Reference frames for modules
- Theory for initial value problem
- Data assimilation

Many other details:

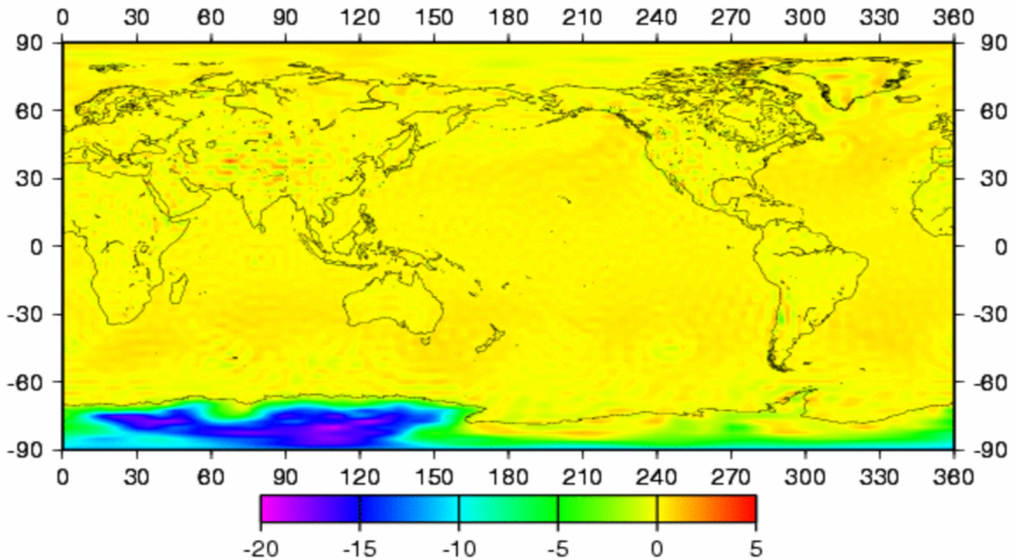
- Spatial resolution of modules (model orography and topography)
- Inconsistencies (mean height: NCEP – ECMWF = 10.7 m)

Challenges

Geopotential minus sea level pressure
2000/01/01/00:



2000/08/01/00:



Challenges:

- Reference frames for modules
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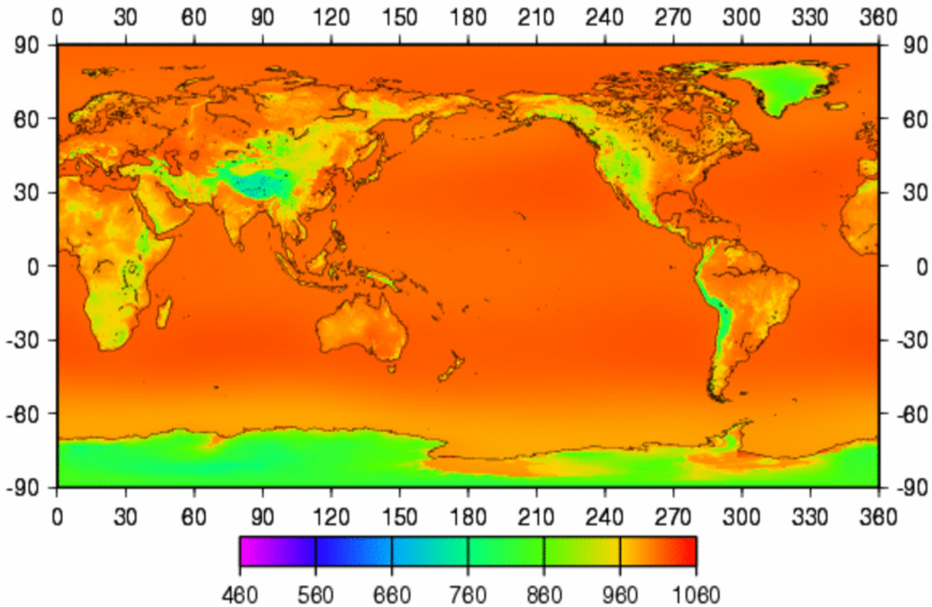
Many other details:

- Spatial resolution of modules (model orography and topography)
- Inconsistencies (mean height: NCEP – ECMWF = 10.7 m)
- Error propagation (example: sea level pressure)

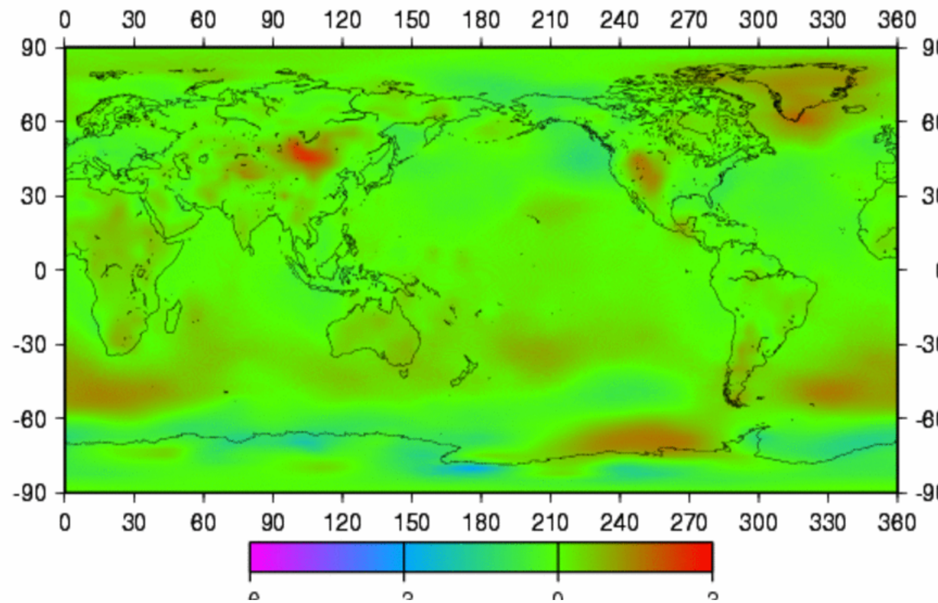
Challenges

Reference air pressure at topographic height

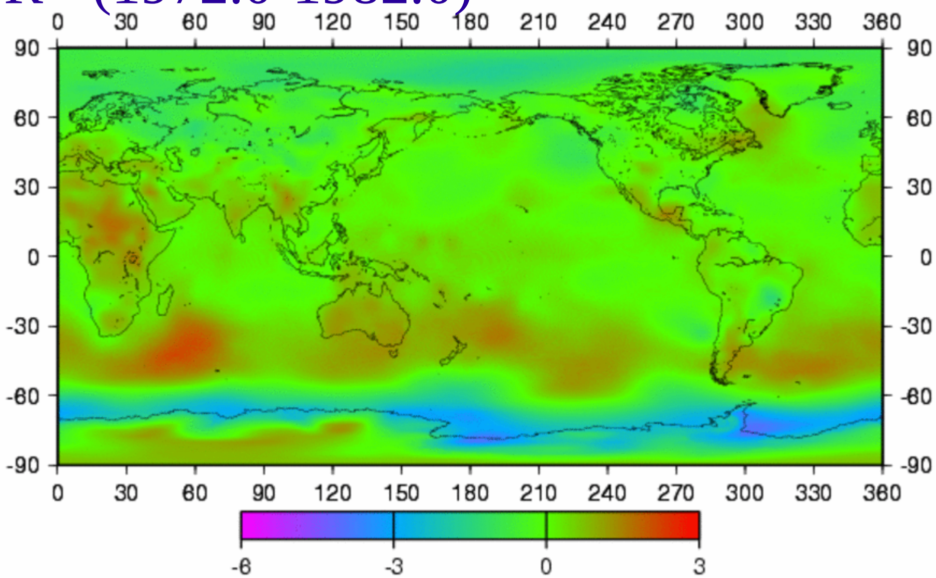
R=1992.0 - 2002.0



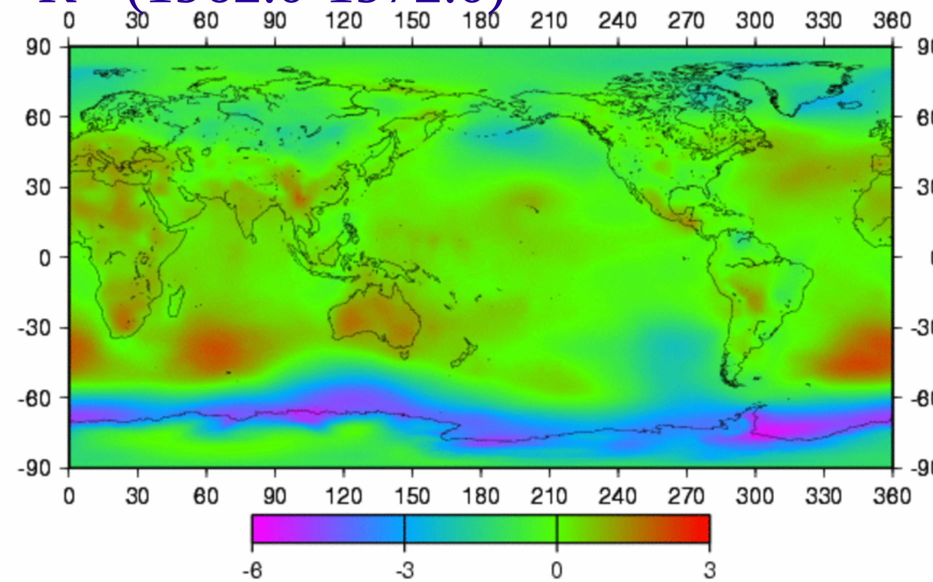
R - (1982.0-1992.0)



R - (1972.0-1982.0)

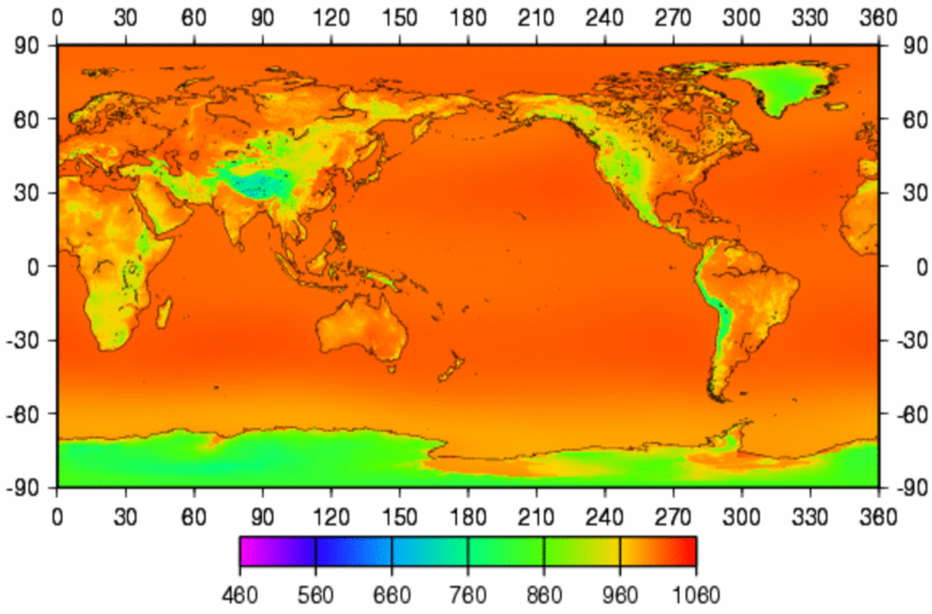


R - (1962.0-1972.0)

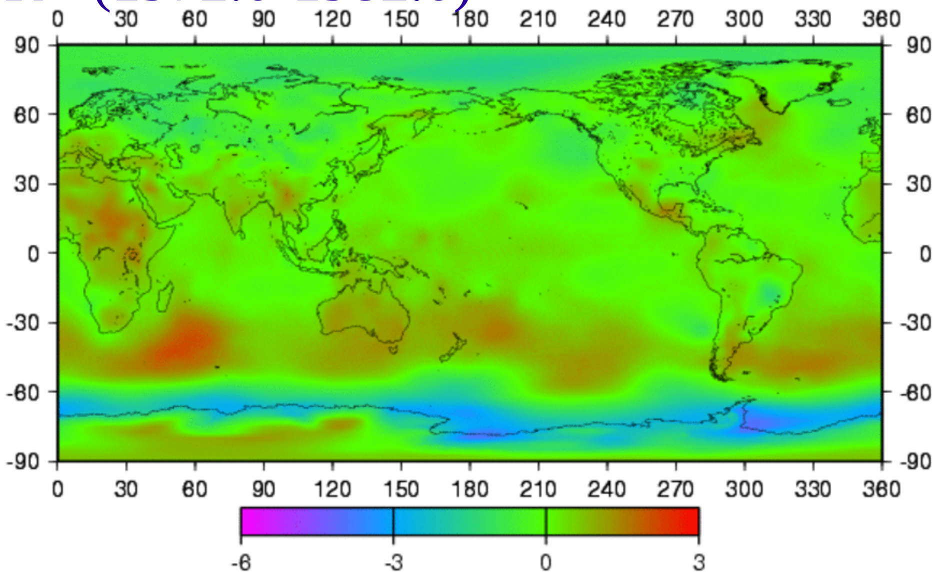


Challenges

Reference air pressure at topographic height
R=1992.0 - 2002.0



R - (1972.0-1982.0)



Challenges:

- Reference frames for modules
- Theory for initial value problem
- Data assimilation

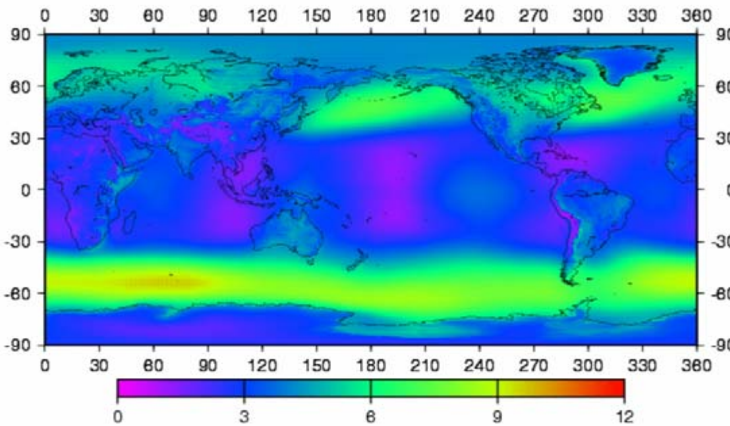
Many other details:

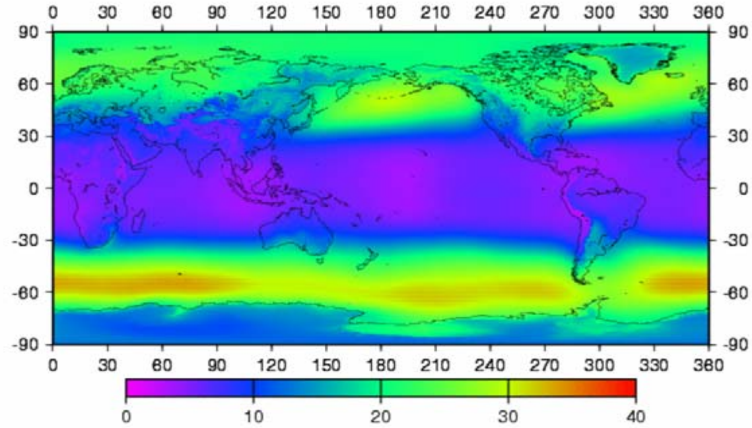
- Spatial resolution of modules (model orography and topography)
- Inconsistencies (mean height: NCEP – ECMWF = 10.7 m)
- Error propagation (example: sea level pressure)
- Choice of reference fields (air pressure, ocean bottom pressure, mean terrestrial water load)

Challenges

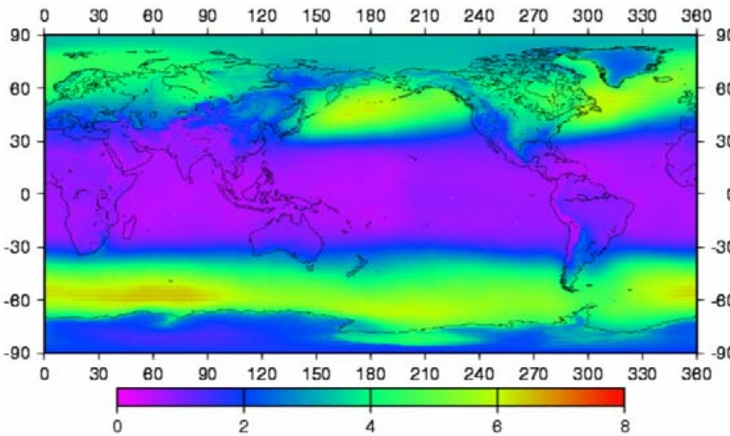
Subdaily variability | Weekly variability

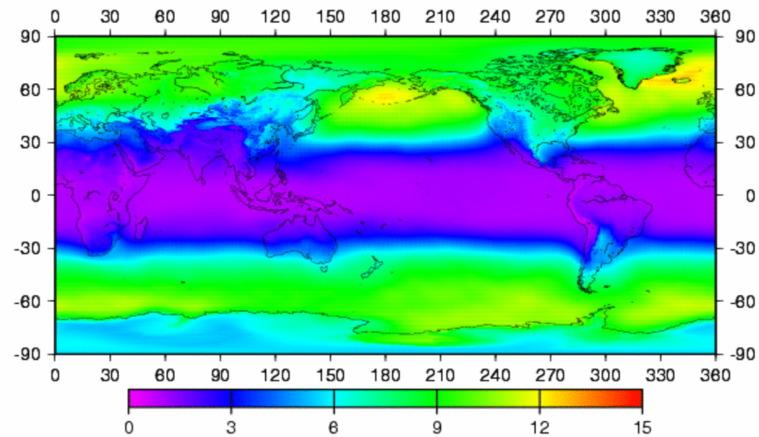
Mean range



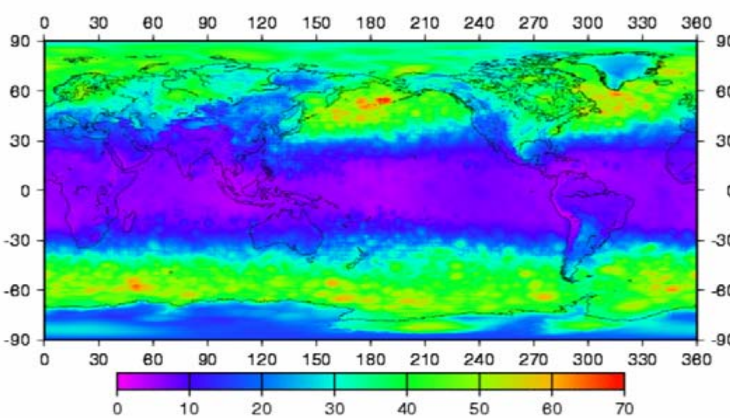


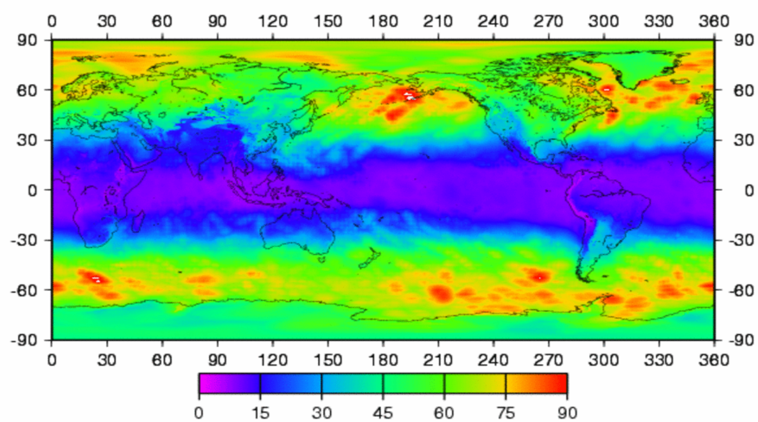
Stand. Dev.





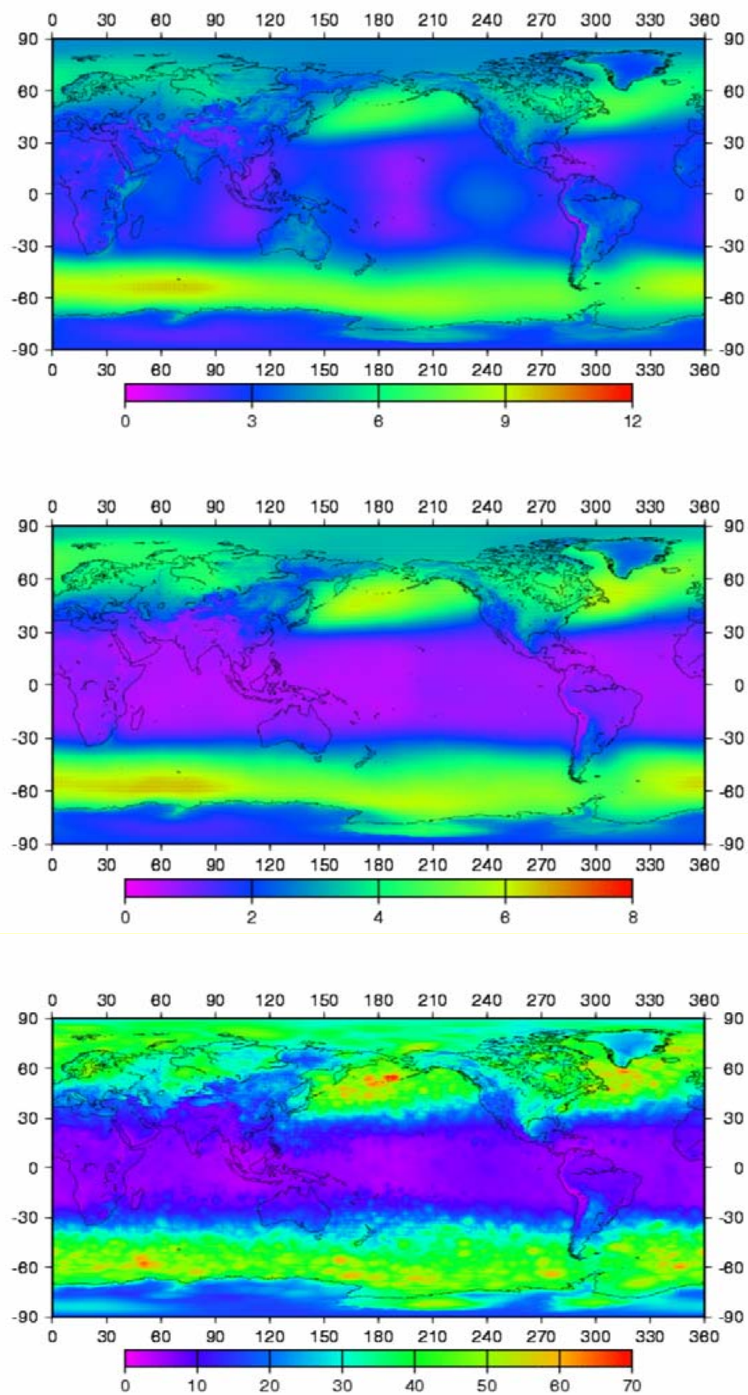
Maximum range





Subdaily variability

Challenges



Challenges:

- Reference frames for modules
- Theory for initial value problem
- Data assimilation

Many other details:

- Spatial resolution of modules (model orography and topography)
- Inconsistencies (mean height: NCEP – ECMWF = 10.7 m)
- Error propagation (example: sea level pressure)
- Choice of reference fields (air pressure, ocean bottom pressure, mean terrestrial water load)
- Inclusion in station motion for analyses?
- Ocean response to atmospheric forcing?

Challenges

S6: Air pressure at topographic height cannot be computed from predicted air pressure at mean sea level due to large errors of this quantity. Instead, air pressure at topographic height has to be computed from air pressure at model orography or interpolated from the geopotential heights of isobars with the former being more accurate.

S7: Interdecadal variation in predicted air pressure at topographic height are found to be of an order significant at the accuracy level of 1 ppb and thus require a careful choice of the conventional reference pressure fields. Moreover, intermodel differences necessitate model-specific reference pressure fields.

S8: For the computation of the global surface pressure anomaly, the response of the ocean to mechanical atmospheric forcing (pressure and wind) has to be modeled with a global hydrodynamical (barotropic) model.

S9: The displacements induced by the atmospheric loading at high latitudes exhibit significant sub-daily and sub-weekly variations.

Immediate Improvements

I1: Extending the **definition of the "regularized coordinates"** to

$$\vec{X}(t) = \vec{X}_0 + \vec{V}_0(\vec{X})(t - t_0) + \delta\vec{X}(\vec{X}_0, t)$$

thus reducing the effect of the global filtering inherent in the current definition.

I2: Improving the operational prediction of displacements due to **atmospheric loading** through (1) better modeling of the **ocean's response** to atmospheric forcing(hydrodynamical barotropic model), (2) a conventional approach to the (model-dependent) **reference surface**(s) for air pressure, and (3) a conventional approach to the handling of **inter-model differences**.

I3: Setting up of an operational computation of **ocean-bottom pressure anomalies** (either model- or GRACE-based) and the computation of the induced surface displacements in support of I1.

I4: Setting up of an operational computation of **terrestrial water storage anomalies** (either model- or GRACE-based or a combination) and the computation of the induced surface displacements in support of I1.

I5: A consistency check based on **mass conservation** should be used to link the anomalies of I2 to I4 together, and to ensure that large errors in mass conservation are detected/avoided.

Recommendations

Comment: All three recommendations are related to progress towards a DREM

Recommendation 1 (atmosphere only**):**

Recognizing that

atmospheric loading is a geophysical process inducing surface displacements at sub-daily to interannual time scales significant at an accuracy level of 1ppb and that

signals of atmospheric loading in the shape, gravity field and rotation of the Earth can be predicted with high accuracy

it is recommended that

as a first step a dynamic reference model is developed and validated that consistently predicts with low latency the atmospheric loading signal in the surface displacement, gravity field and rotation of the Earth and that

these predictions are taken into account in the determination of the ITRF as well as the products providing low-latency access to ITRF.

Recommendations

Recommendation 2 (hydrological cycle):

Recognizing that

mass redistribution in atmosphere, oceans, and terrestrial hydrosphere are inherently related through processes in the global hydrological cycle and that

these mass redistributions cause surface displacements at sub-daily to interannual time scales significant at an accuracy level of 1 ppb and that

the feedback between the individual components (reservoirs) of the hydrological cycle as well as the solid Earth also cause significant signals in the shape, gravity field and rotation of the Earth

it is recommended that

a dynamic Earth model is developed and validated that consistently predicts the geodetic signals of mass redistribution in the global hydrological cycle and that accounts for the geophysical interactions between the reservoirs of the hydrological cycle and the solid Earth.

Recommendations

Recommendation 3 (all relevant geophysical processes**):**

Recognizing that

monitoring of point motion and detection of “anomalous motion”' are key application of a modern global reference frame and space geodetic techniques, and that

for many applications a predictive reference frame is required, and that

such a reference frame needs to be based on a Dynamic Reference Earth Model(DREM)

it is recommended that

a DREM is developed that accounts for all know geophysical processes significant at the level of 1ppb and that predicts consistently the signals in Earth shape, rotation and gravity field caused by these processes.